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Disk-Planet Interaction: Spiral Arms, Gap Opening, Observational Prospects

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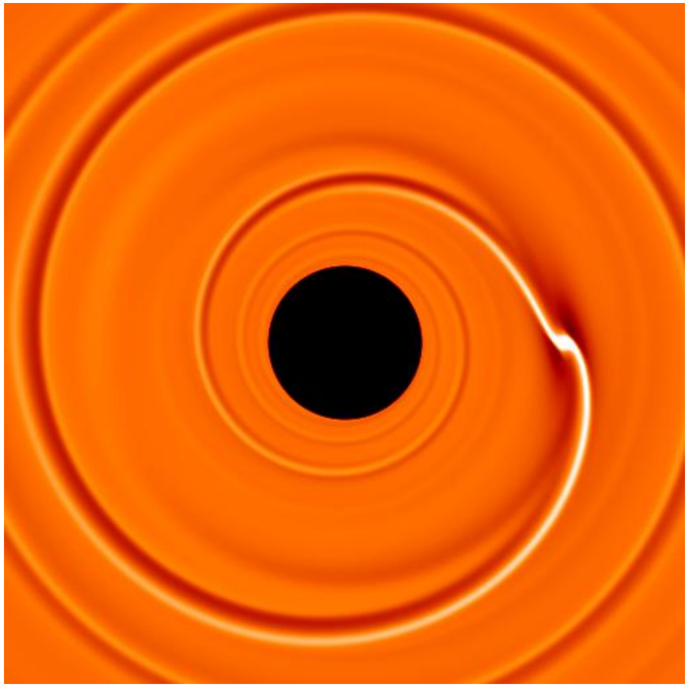
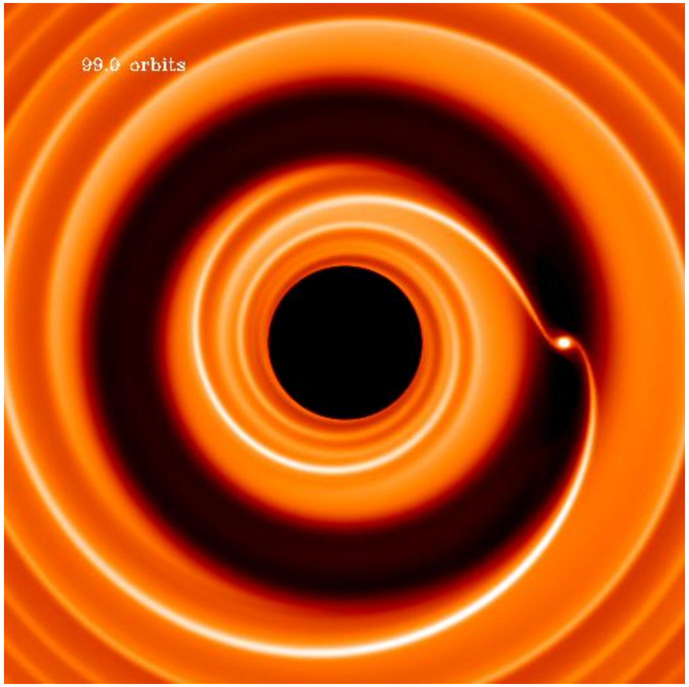
1. Introduction
2. Fundamentals of spiral density wave
3. Gap formation in a protoplanetary disk
4. Observational prospects

Disk-Planet Interaction

- Gravitational Interaction between a Planet and a Disk
  - And nothing more…





http://www.maths.qmul.ac.uk/~masset/moviesmpegs.html

Why Disk-Planet Interaction?

- Radial migration of the planet
  - Planets can migrate significantly before the dispersal of the gas disk
  - Impact on planet formation theory
- Redistribution of the gas in the disk
  - Planets can form a spiral density wave, gap, possibly inner hole…
  - Observational predictions

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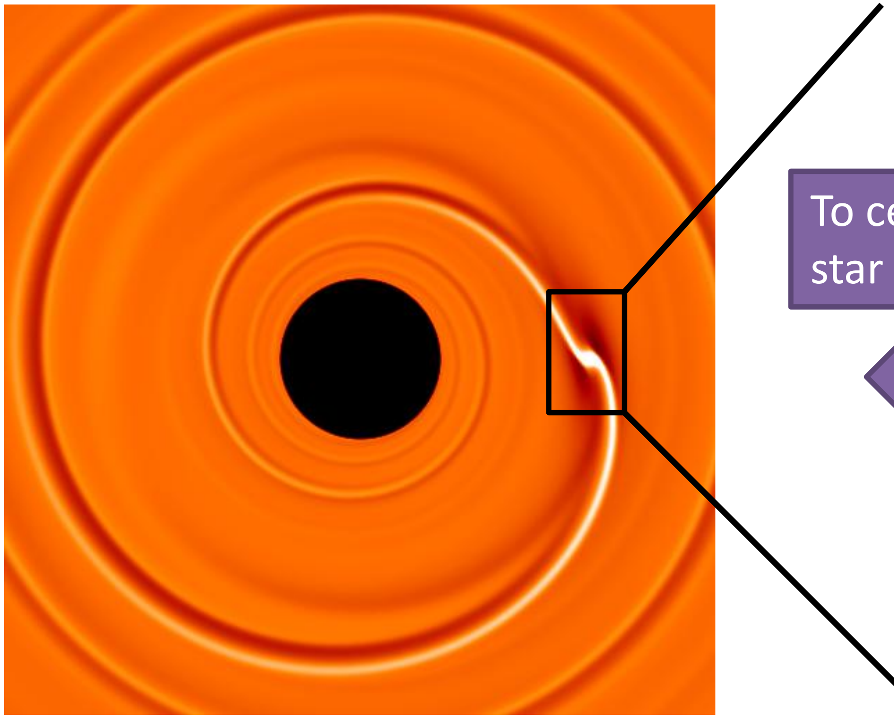
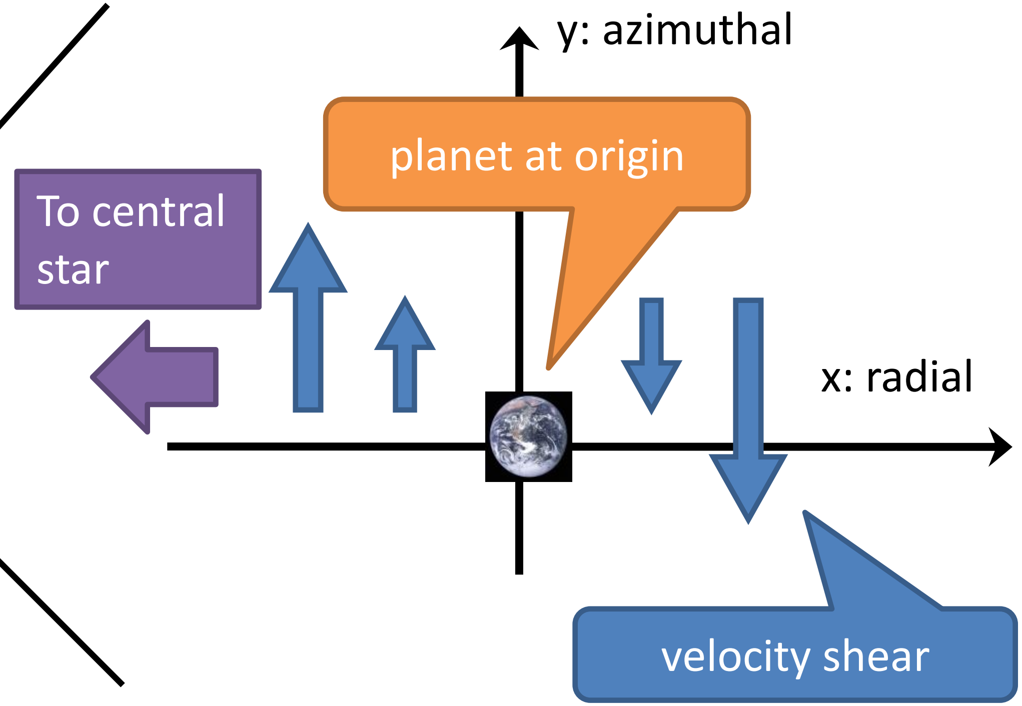
Problem Setup

- Consider the simplest case
  - A planet in a circular orbit in a circular disk
- We expect a steady state ***in a rotating frame with the planet***

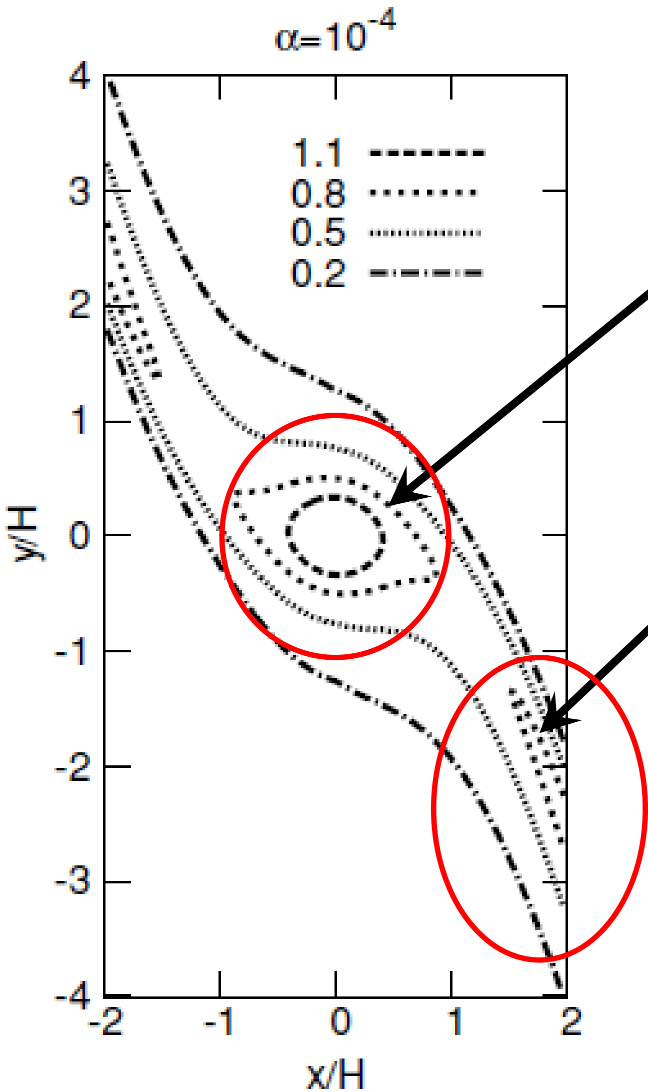
Shearing-sheet
close-up of the vicinity of the planet





$$v_y = -\frac{3}{2}\Omega_{\mathrm{p}} x$$

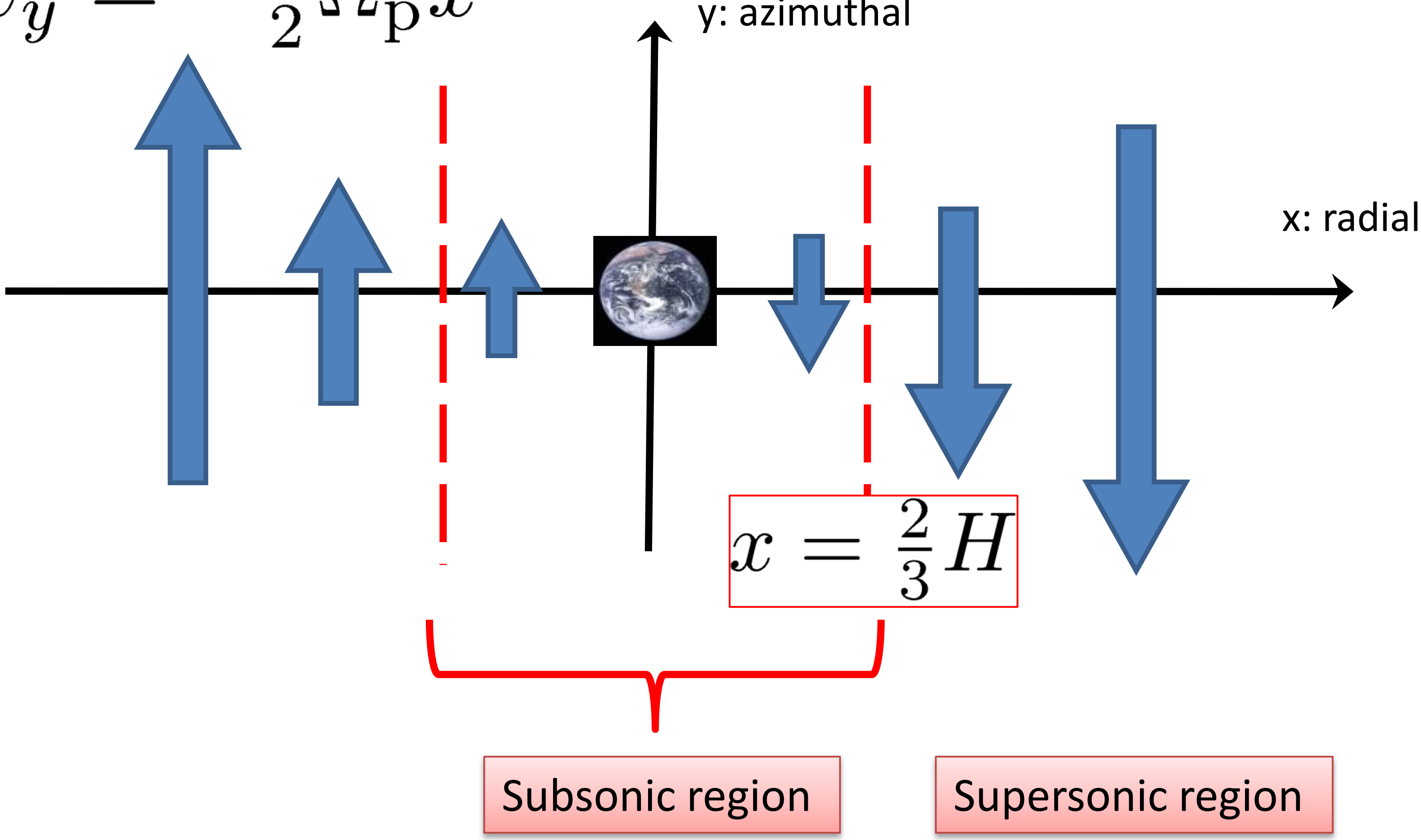
Surface Density Perturbation



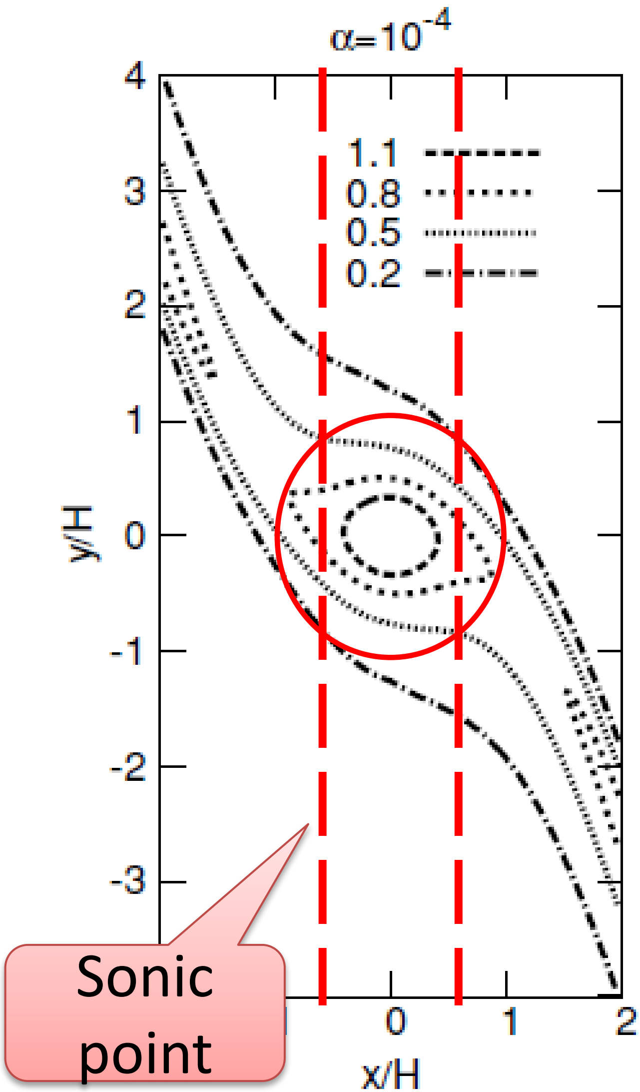
- Spherical structure around the planet
- Spiral density wave launched a little far away from the planet

Background Velocity Field

$$v_y = -\frac{3}{2}\Omega_{\rm p} x$$



Response of Gas in Subsonic Region



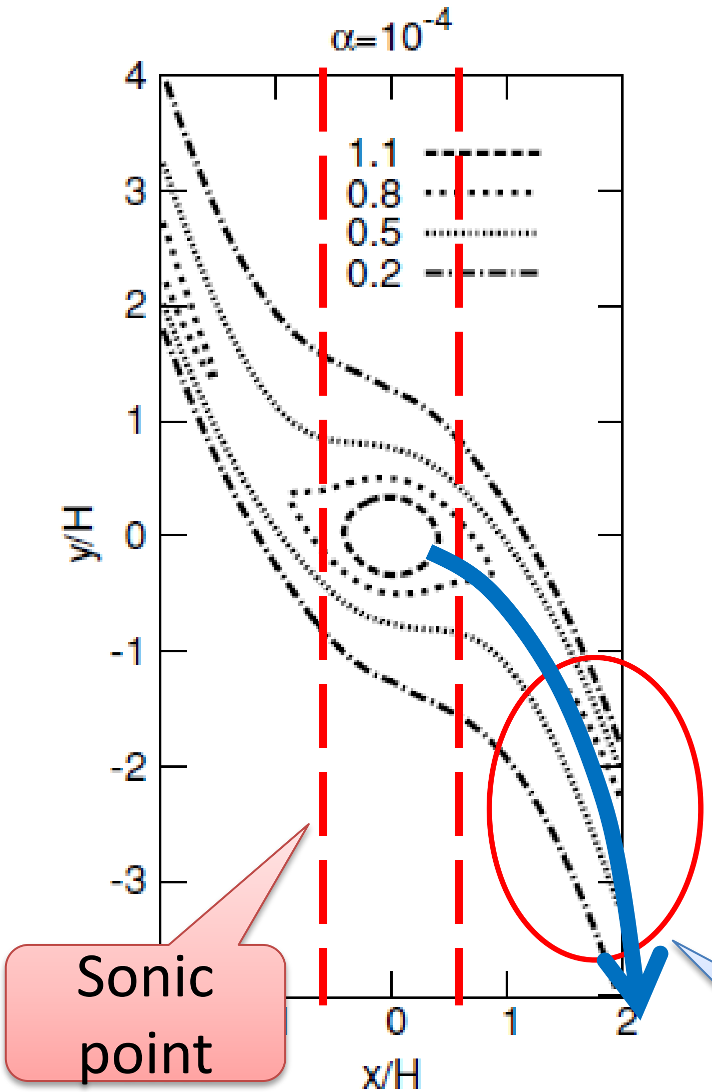
- Hydrostatic equilibrium
- A little tilted due to shear, viscosity…

$$\frac{GM_{\rm p}}{d} \sim c^2 \frac{\delta\Sigma}{\Sigma}$$

Planet's gravitational energy
d: distance to the planet

Gas thermal energy perturbation

Response of Gas in Supersonic Region



- Density perturbation "carried away" by shear

Characteristic curve (steady state in a supersonic flow):

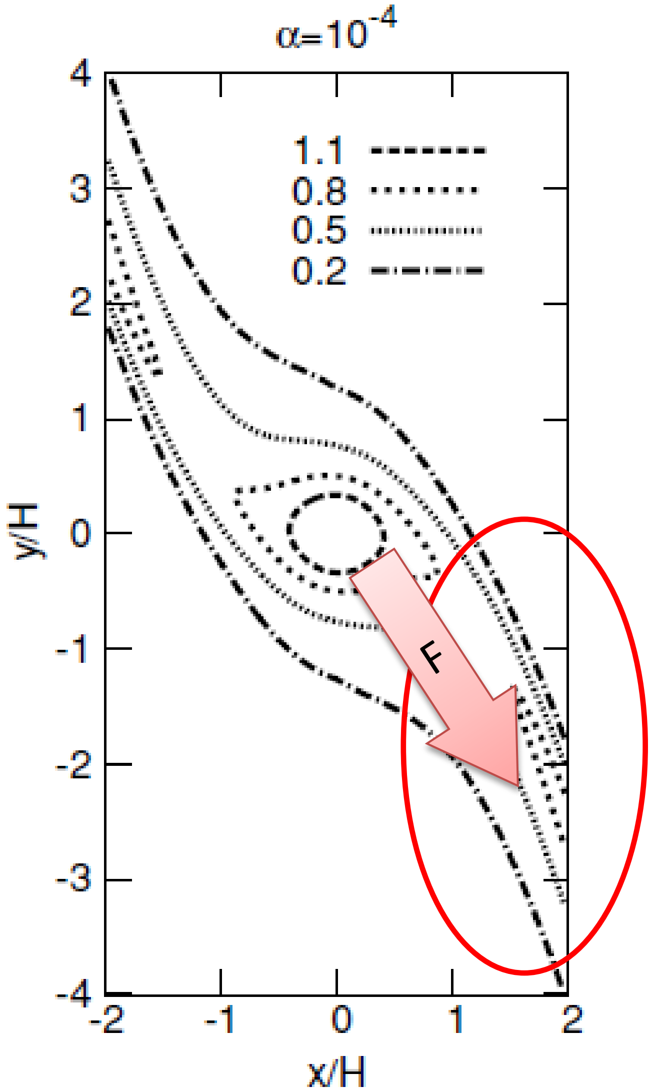
$$\left(\frac{dy}{dx}\right)_{\pm} = \frac{v_x v_y \pm c\sqrt{v^2 - c^2}}{v_x^2 - c^2}$$

Landau & Lishitz

Gives the shape of the spiral:

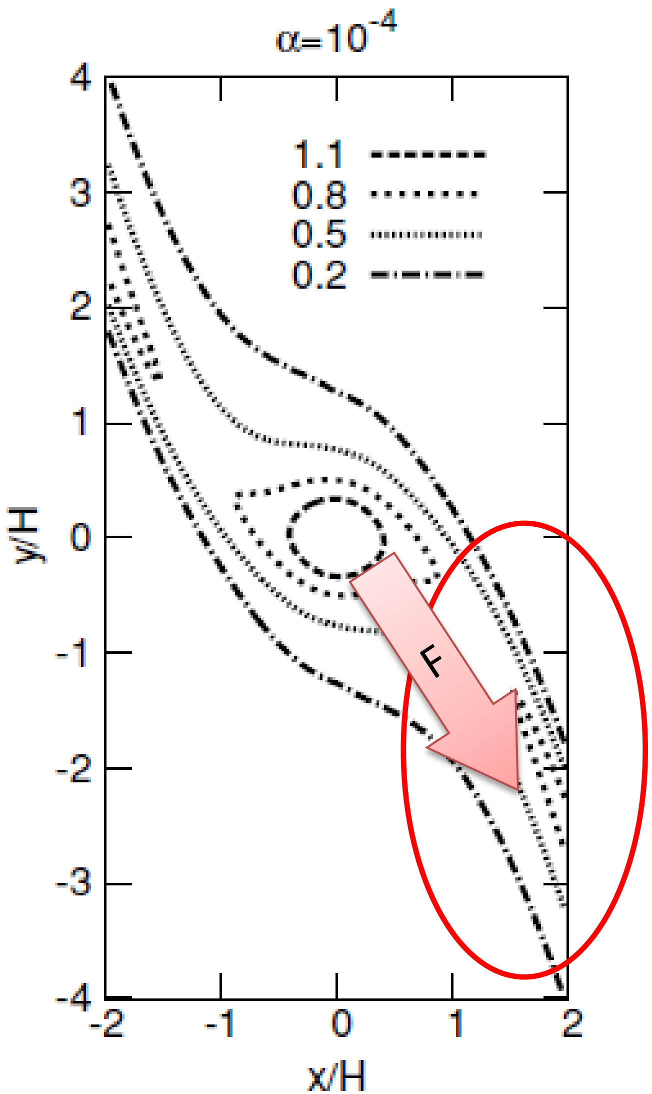
$$y \sim -\frac{3}{4}\frac{x^2}{H} + y_0$$

Back reaction onto the Planet



- Type I migration
- Perturbed surface density exerts gravitational force to the planet

Order-of-Magnitude of type I rate (1)

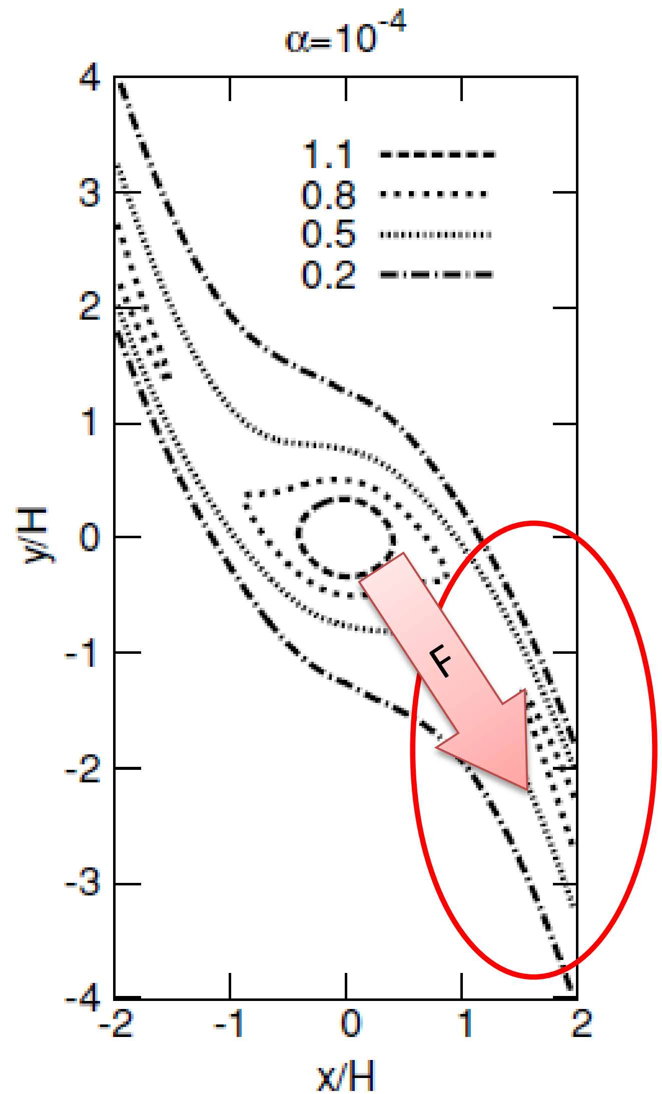


Significant asymmetry in the y-direction at the sonic point: distance ~H away from the planet

$$\frac{GM_{\rm p}}{H} \sim c^2 \frac{\delta\Sigma}{\Sigma}$$

Gives you the estimate of surface density perturbation

Order-of-Magnitude of type I rate (2)



Calculate force from the surface density perturbation

$$F \sim \frac{G M_{\rm p}(\delta\Sigma H^2)}{H^2}$$

NOTE: this force is from one side of the planet

Differential Force:

$$\boxed{F \sim \frac{G M_{\rm p}(\delta\Sigma H^2)}{H^2} \times \frac{H}{r}}$$

Order-of-Magnitude of type I rate (3)

Now you know the force, you can calculate the torque and migration rate

$$T \sim r_p F \sim \frac{dL}{dt} \sim M_p r_p \Omega_p \frac{dr_p}{dt}$$

Migration rate is then given by:

$$\boxed{\frac{1}{r_\mathrm{p}}\frac{dr_\mathrm{p}}{dt} \sim \left(\frac{M_\mathrm{p}}{M_*}\right)\left(\frac{\Sigma r_\mathrm{p}^2}{M_*}\right)\left(\frac{r_\mathrm{p}}{H}\right)^2 \Omega_\mathrm{p}}$$

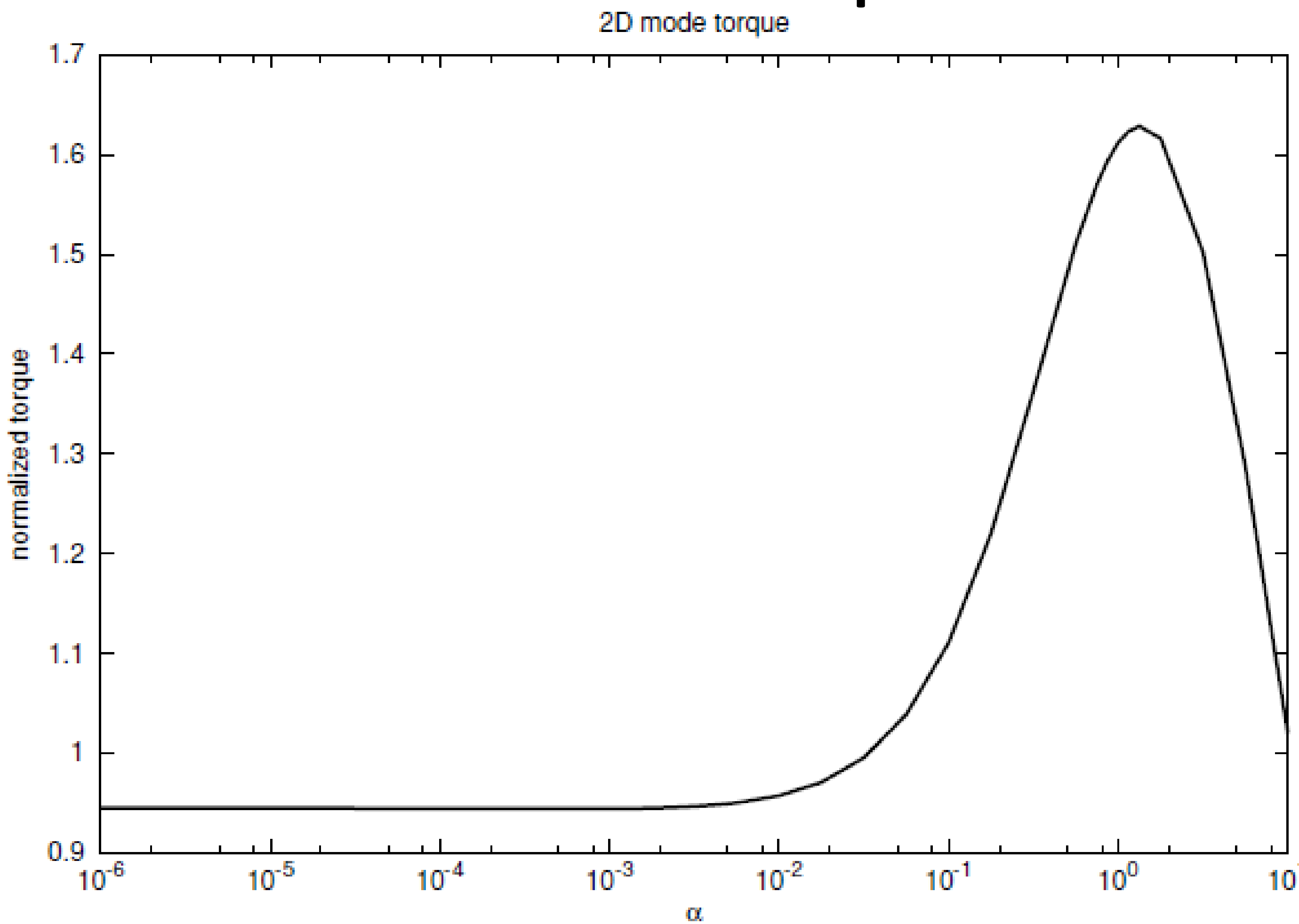
Typically, 10^5 yrs for $10M_E$ at 5AU

Tanaka et al. 2002

Some Recent Studies on Migration

- Modification to migration rate and direction due to various physical processes in the disk
  - Viscosity
    - Masset (2001, 2002), Paardekooper and Papaloizou (2009), Muto and Inutsuka (2009)…
  - Self-gravity
    - Baruteau and Masset (2008)…
  - Thermal physics
    - Paardekooper and Mellema (2006), Baruteau and Masset (2008), Paardekooper and Paploizou (2008), Kley and Crida (2008), Bitsch and Kley(2010), Paardekooper et al. (2010)…
  - Turbulence
    - Nelson and Papaloizou (2004), Oishi et al. (2007), Baruteau and Lin (2010), Baruteau et al. (2011)…
  - Ordered (stable) magnetic field
    - Terquem (2003), Fromang et al. (2005), Muto et al. (2008)…
  - Planet Eccentricity and Inclination
    - Papaloizou and Larwood (2000), Tanaka and Ward (2004), Cresswell and Nelson (2006), Cresswell et al. (2007), Bitsch and Kley (2010), Muto et al. (2011), Rein (2011)…

Effect of Viscosity on One-sided Lindblad Torque



Muto and Inutsuka 2009

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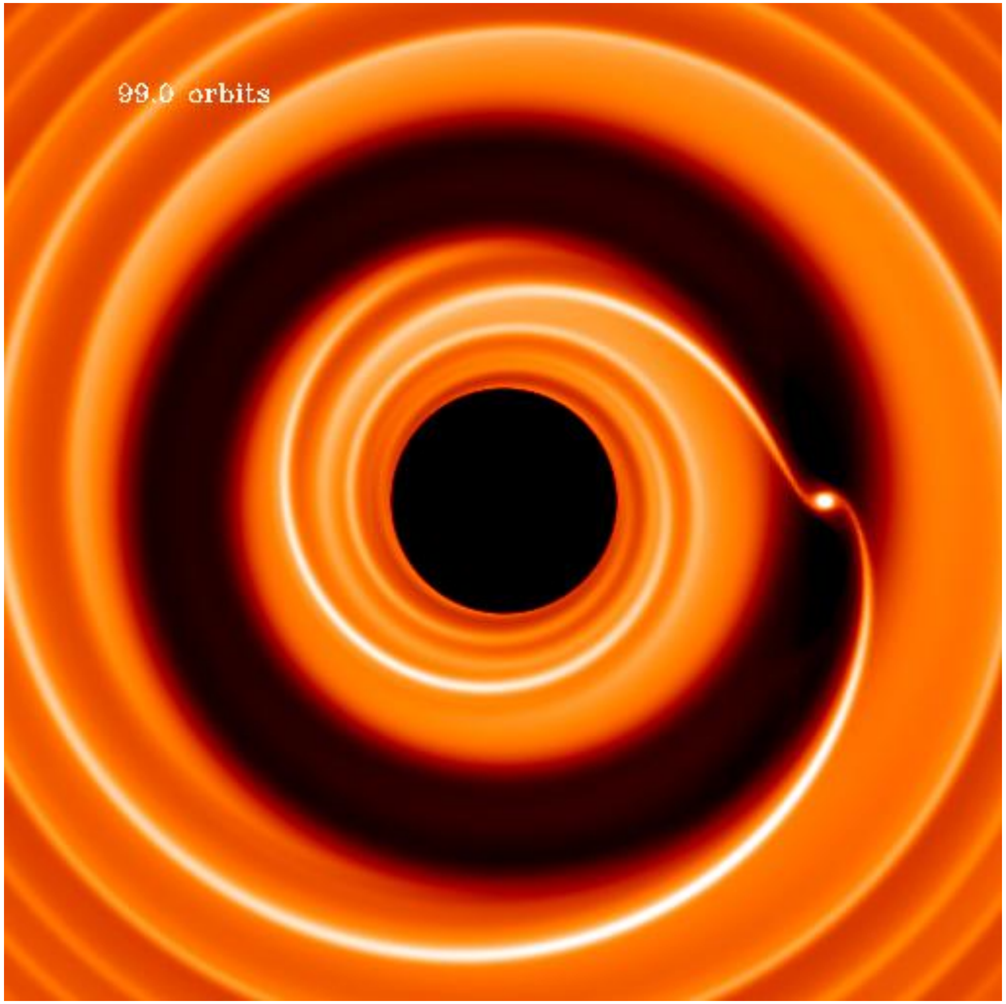
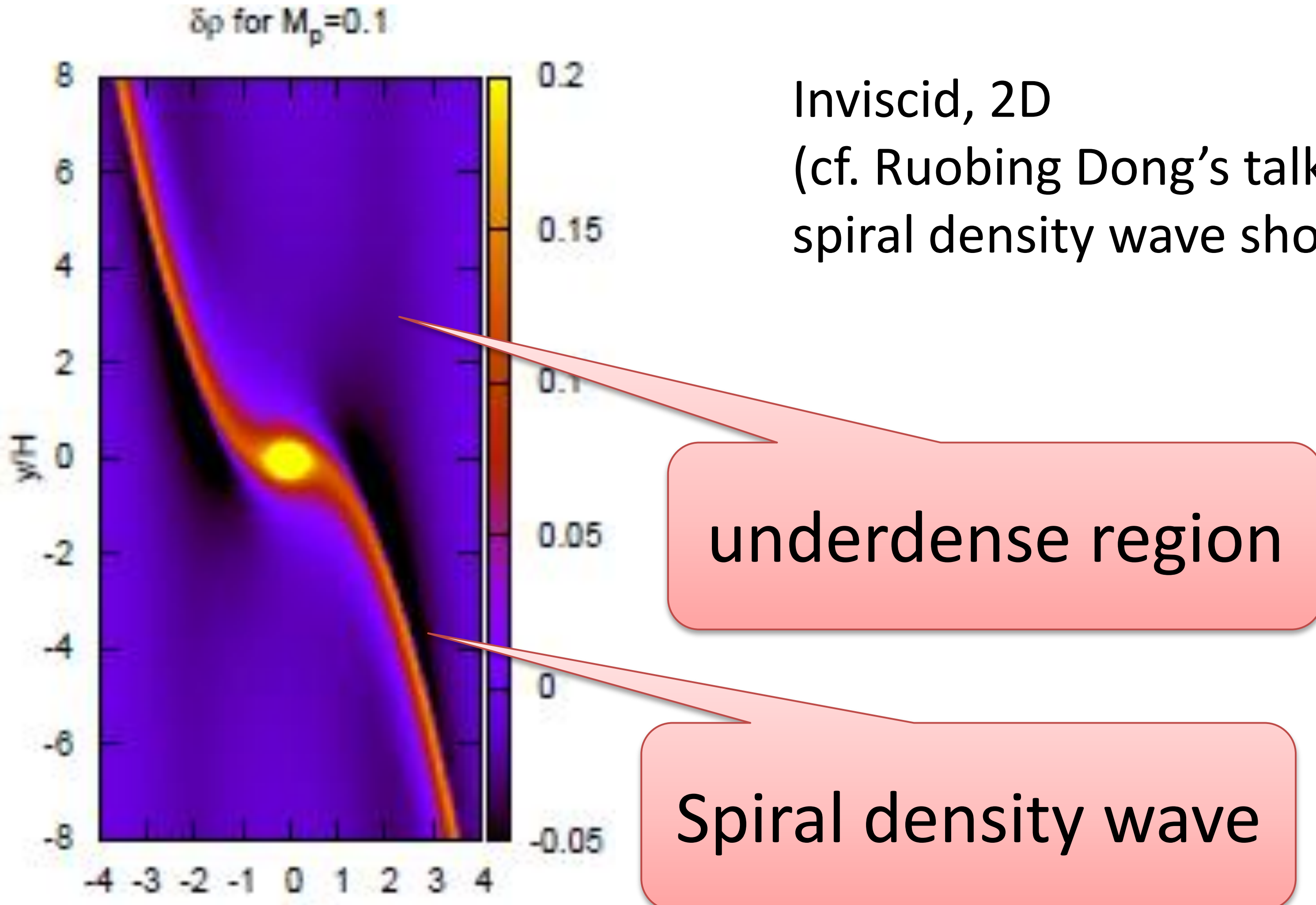
A Planet Opens a Gap



Physics of Gap Formation

- Spiral density wave carries angular momentum
- Spiral density wave damps eventually:
  - Disk viscosity, shock formation…
  - Angular momentum exchange between the planet and the disk
- Gap formation
  - Study "minimum" gap-opening process

Shearing-sheet Simulation

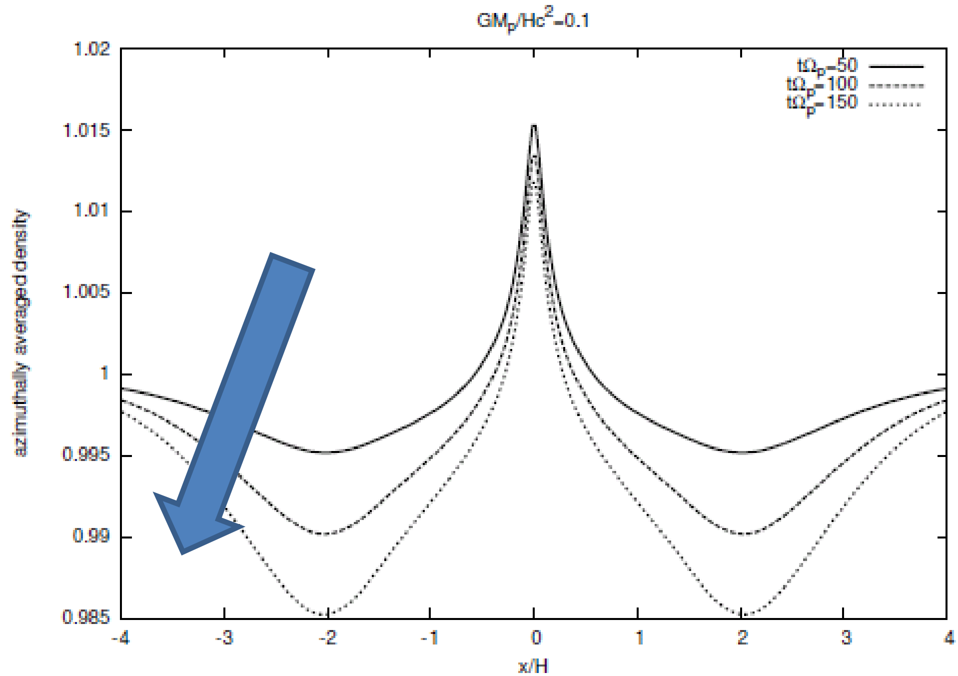


$$GM_p/Hc^2 = 0.1$$

Inviscid, 2D
(cf. Ruobing Dong's talk for spiral density wave shock)

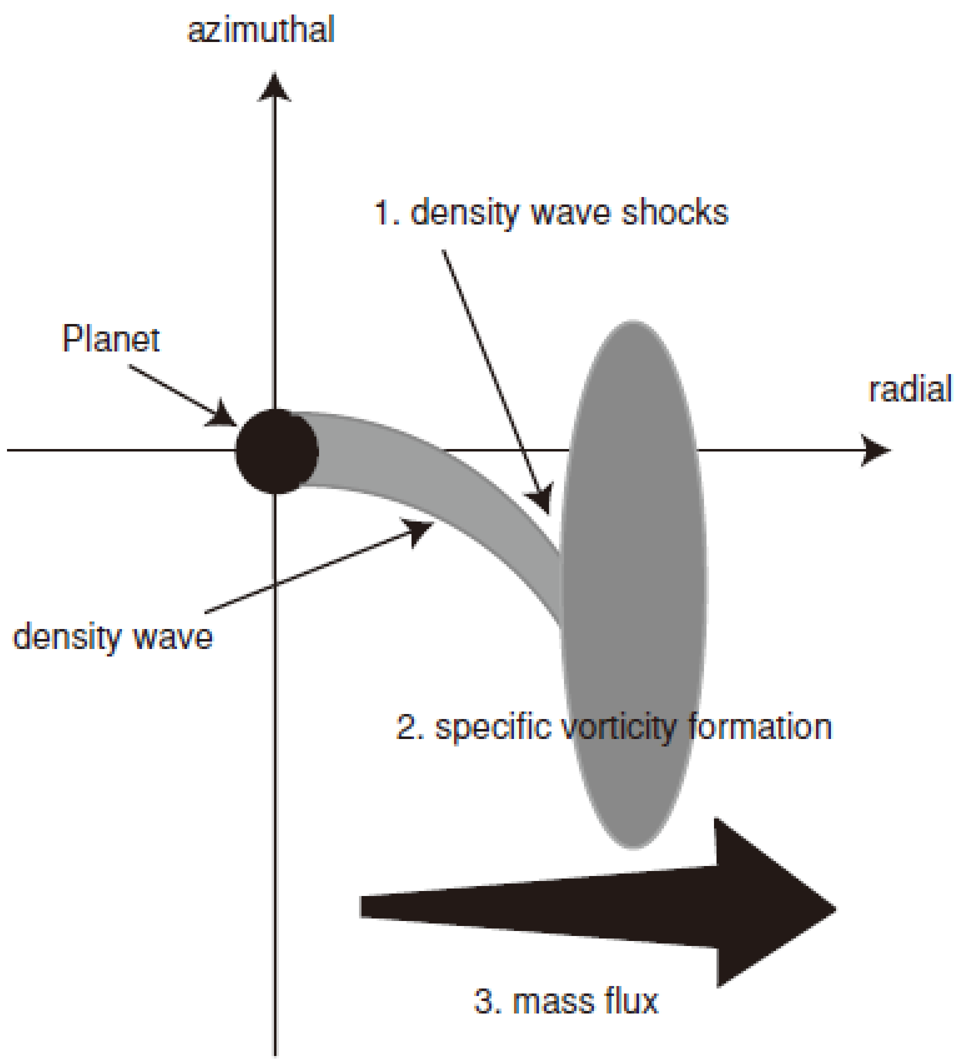
Gap formation

Evolution of azimuthally-averaged density



The disk is not quite in a steady state

Gap-opening by Shock Dissipation



- "Minimum" gap-opening process
  - Does not incorporate any explicit viscosity

Gap-opening Mass

Gap-opening timescale (derived in numerical simulation) is compared with the type I migration rate over the gap width (~H)

$$\boxed{\frac{M_{\rm p}}{M_*} > 8 \times 10^{-5} \left(\frac{H/r_{\rm p}}{0.05} \right)^3 \frac{\Sigma}{2\times 10^3 {\rm g/cm^3}} \left(\frac{r_{\rm p}}{1{\rm AU}} \right)^2 \left(\frac{M_*}{M_\odot} \right)^{-1}}$$

Planets with mass lower than this limit are still able to open a gap if type I migration is halted

Muto et al. (2010)

Effects of Viscosity

- Viscosity must be very small for the shock-induced gap-opening to act

$$\alpha \lesssim 2.8 \times 10^{-5} \left(\frac{H/r_{\rm p}}{0.05} \right)^{-5} \left(\frac{M_{\rm p}/M_*}{2 \times 10^{-5}} \right)^{2}$$

- Gap shape determined by planetary torque vs viiscous diffusion:
  - Crida's criterion

$$\frac{3}{4}\frac{H}{R_H} + \frac{50}{q\mathcal{R}} \lesssim 1$$

Crida et al. (2006)

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Typical Parameters of PP Disks

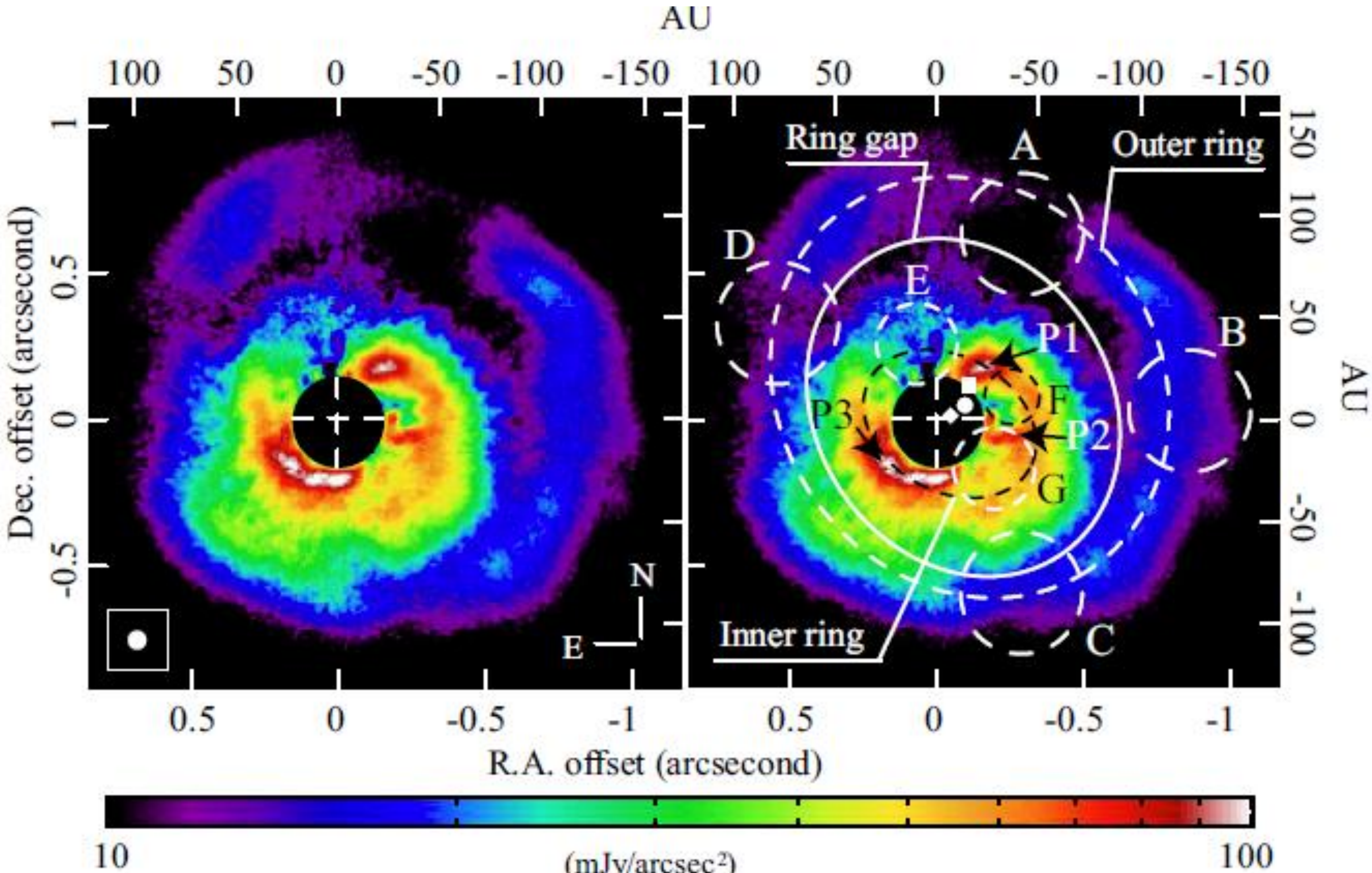
- Disk aspect ratio is ~0.1-0.2 at 100AU
- Therefore, disk scale height may be

$$H = 15\mathrm{AU}\left(\frac{r}{100\mathrm{AU}}\right)^{5/4}$$

- Corresponds to 0.1” if the disk is at 150pc
- 8m-telescopes, TMT, or ALMA can resolve the structure comparable to the disk scale height at outer disk
- Direct imaging can probe the dynamical processes in the disk

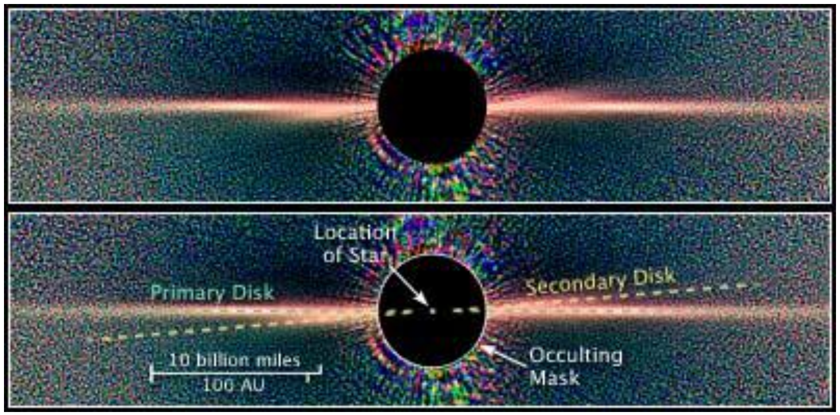
Recent Result by Subaru/HiCIAO

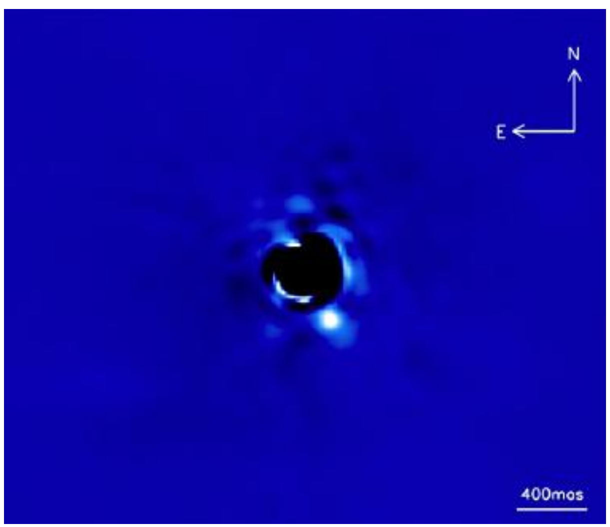
Direct imaging of the disk around AB Aur



Hashimoto, Tamura, Muto et al. (2010)

βPic

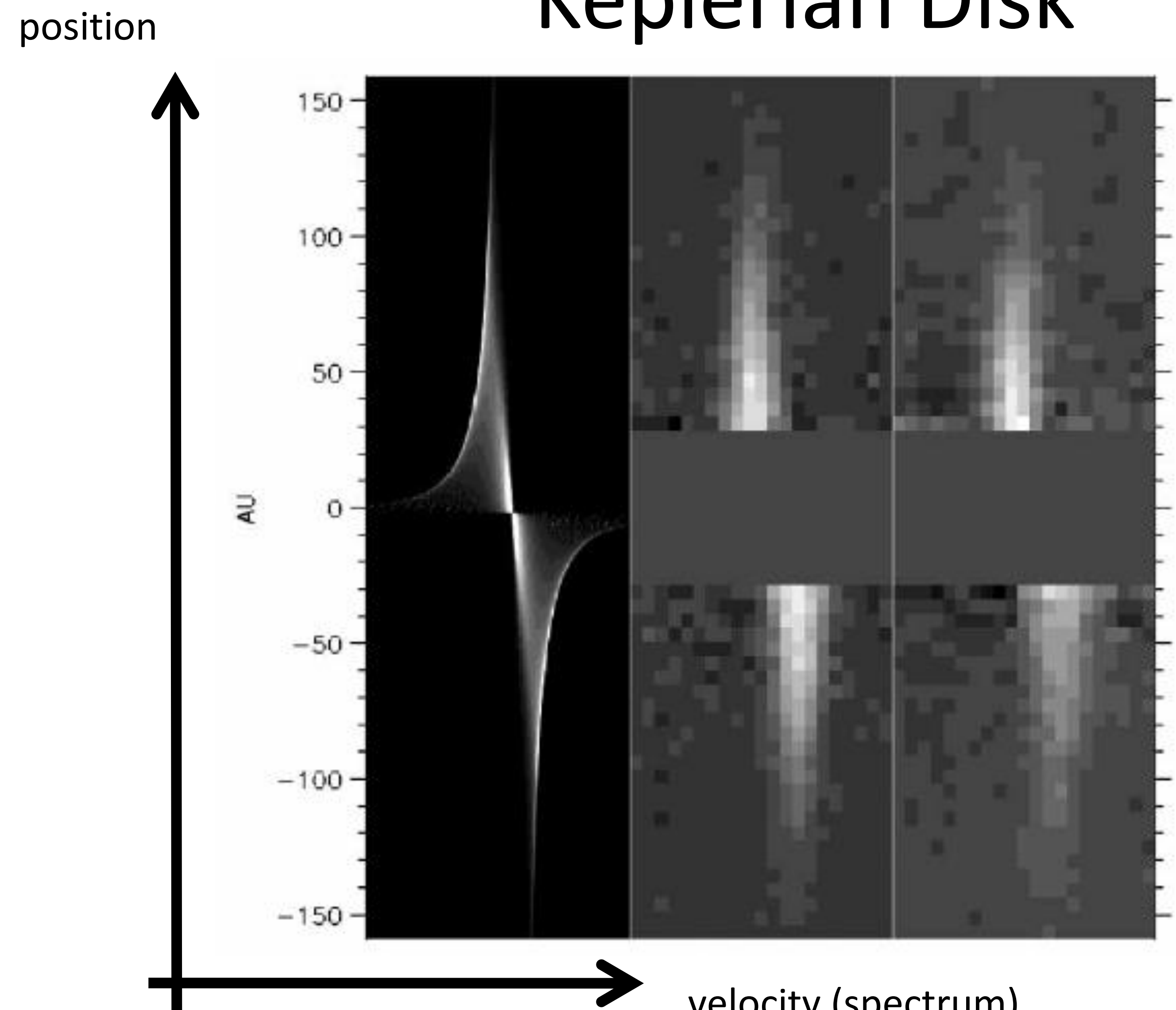




- Tenuous circumstellar dust disk with gas components
- Large scale edge-on disk imaged
- Planet at ~10AU
- See Alexis Brandeker’s talk on the first week

*NASA, ESA, D. Golimowski (Johns Hopkins University), D. Ardila (IPAC), J. Krist (JPL), M. Clampin (GSFC), H. Ford (JHU), and G. Illingworth (UCO/Lick) and the ACS Science Team
**Lagrange et al. 2010

Observation of (optically thin) Keplerian Disk



Olofsson et al. 2001

Summary

- Gravitational interaction between planet and disk
  - Spiral arms, gap formation, planetary migration
  - Basic framework of spiral arms and type I migration reviewed
  - Gap-opening due to the spiral shock
- Observational prospects
  - Direct imaging observations can reveal the structure with ~H at outer (~100AU) disk
  - Planet signature in βPic disk?